ATLAS EXPERIMENT

CMS

Universidade do Minho
Escola de Ciências

LIP

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

EFT studies in the top quark sector (and beyond)

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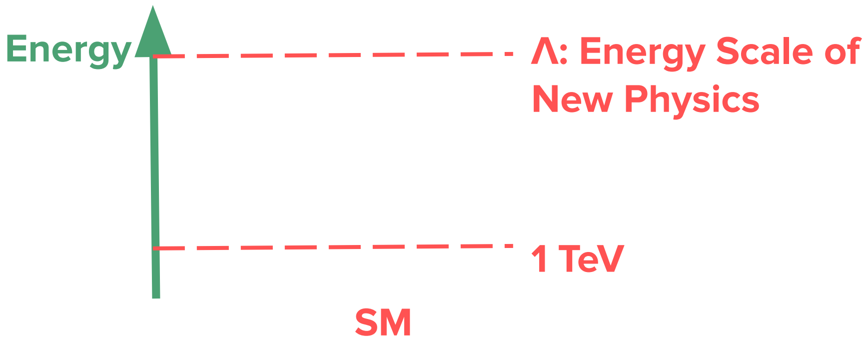
Energy Frontier Workshop - Restart [Snowmass]
virtual world, September 2nd 2021

FCT Fundação para a Ciência e a Tecnologia
CERN/FIS-PAR/0002/2019
CERN/FIS-PAR/0024/2019

Effective field theory
in the top-quark sector (and beyond)

- An **EFT approach** in top-quark sector is being pursued at the LHC since almost the beginning of data taking
  - using precision measurements and searches for rare events as a probe for physics beyond the Standard Model
  - Experience in the LHC *top* WG and, more recently, in the LHC *EFT* WG

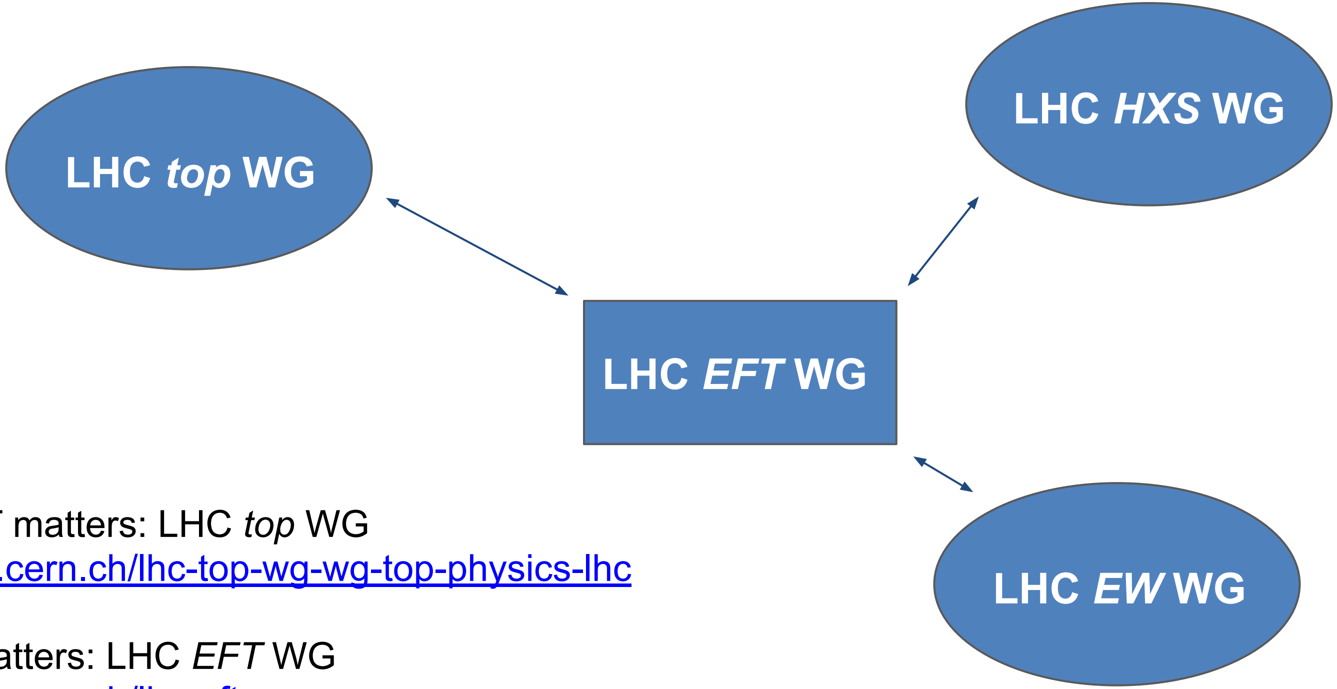


SM effective field theory:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

typically assuming Λ = 1 TeV

Effective field theory
in the top-quark sector (and beyond)



- Top related EFT matters: LHC *top* WG
  https://lpcc.web.cern.ch/lhc-top-wg-wg-top-physics-lhc
- General EFT matters: LHC *EFT* WG
  https://lpcc.web.cern.ch/lhc-eft-wg

Effective field theory in the top quark sector

$t\bar{t}$ operators

- Observables: **R**ate, **D**istribution, **A**symmetries, **P**olarization, **S**pin correlation

Linear

$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\,\widetilde{\phi}\,G^A_{\mu\nu}$$
$$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$
$$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$
$$O^{8}_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i)$$
$$O^{8}_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i)$$
$$O^{8}_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i)$$
$$O^{8}_{Qd} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i)$$
$$O^{8}_{tq} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$

Quadratic

$$O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$$
$$O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$$
$$O^{1}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$$
$$O^{1}_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ;$$
$$O^{1}_{Qu} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$$
$$O^{1}_{Qd} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$$
$$O^{1}_{tq} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)\ ;$$

Four-fermion in V/A basis

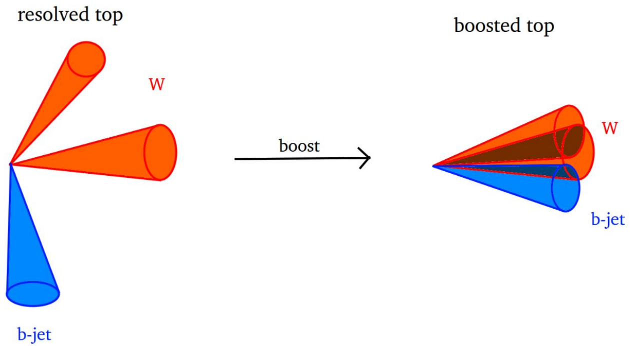
$$4\,C^{u,8}_{VV} = C^{1,8}_{Qq} + C^{3,8}_{Qq} + C^{8}_{tu} + C^{8}_{tq} + C^{8}_{Qu}$$
$$4\,C^{u,8}_{AA} = C^{1,8}_{Qq} + C^{3,8}_{Qq} + C^{8}_{tu} - C^{8}_{tq} - C^{8}_{Qu}$$
$$4\,C^{u,8}_{AV} = -(C^{1,8}_{Qq} + C^{3,8}_{Qq}) + C^{8}_{tu} + C^{8}_{tq} - C^{8}_{Qu}$$
$$4\,C^{u,8}_{VA} = -(C^{1,8}_{Qq} + C^{3,8}_{Qq}) + C^{8}_{tu} - C^{8}_{tq} + C^{8}_{Qu}\,.$$

Similar for down-type quarks
and color singlets

[slide by Cen Zhang]

$t\bar{t}$ operators: differential measurements

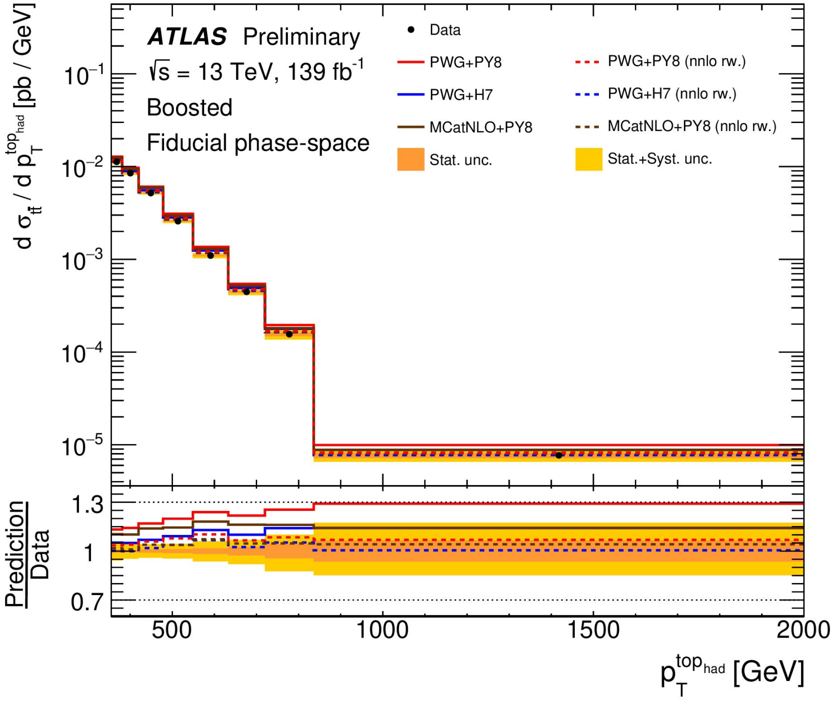
- Hadronically decaying boosted top quarks
  - $p_T \gtrsim 300$ GeV
  - decay products start to overlap - different identification methods are needed
  - new physics can alter top quark production especially in the boosted phase space
  - boosted top quarks identified within large-R jets
    - reduced combinatorics
    - possibility to use large-R jet triggers



[ATLAS-CONF-2021-031]

$t\bar{t}$ operators: differential measurements

- Unfolded to particle level using iterative Bayesian unfolding
- Main uncertainty: Signal modeling



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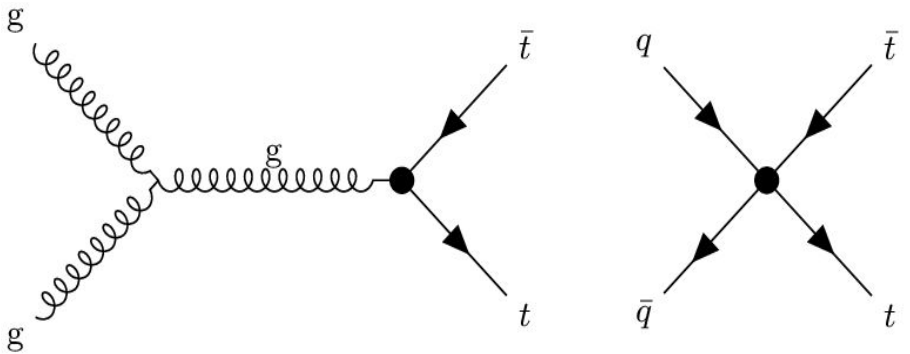
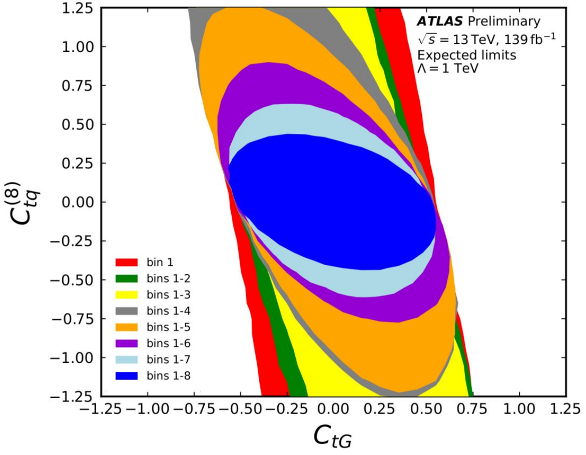
$t\bar{t}$ operators: differential measurements



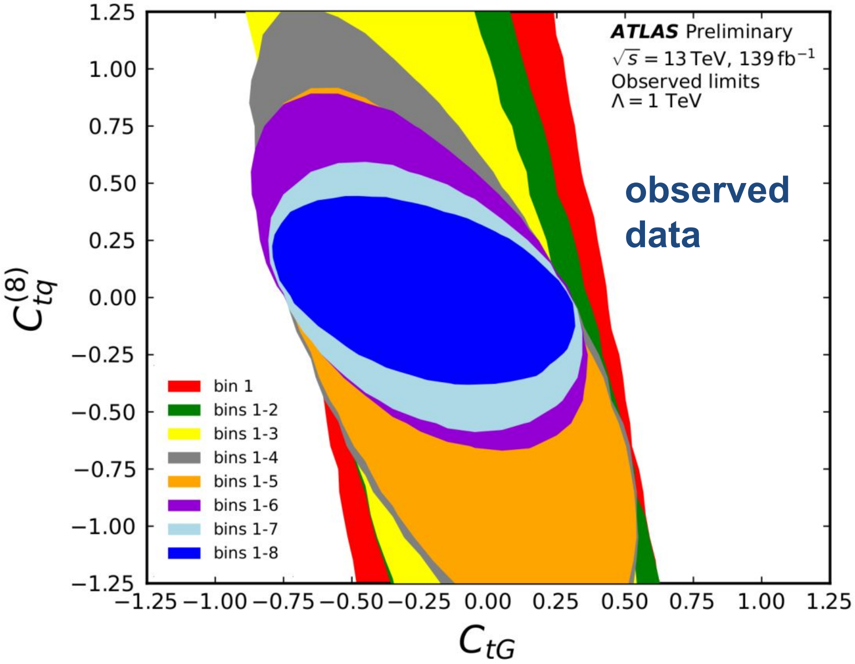
$$\sigma^j(C_{tG}, C_{tq}^{(8)}) = p_0^j + p_1^j \cdot C_{tG} + p_2^j \cdot C_{tq}^{(8)} + p_3^j \cdot (C_{tG})^2 + p_4^j \cdot (C_{tq}^{(8)})^2 + p_5^j \cdot C_{tG} \cdot C_{tq}^{(8)}$$

[ATLAS-CONF-2021-031]

$t\bar{t}$ operators: differential measurements

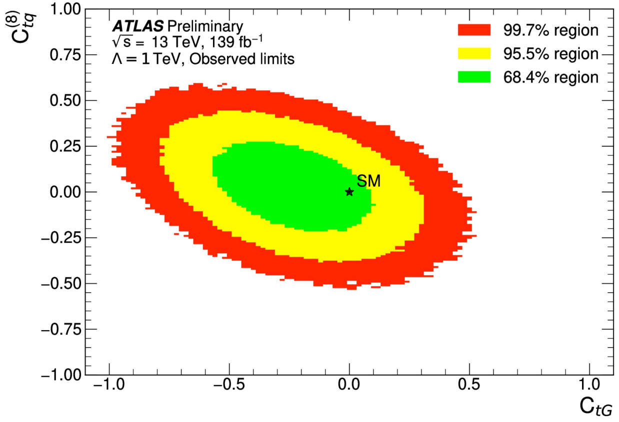


SM simulation



[ATLAS-CONF-2021-031]

$t\bar{t}$ operators: differential measurements



Wilson coefficient	Marginalised 95% intervals		Individual 95% intervals		
	Expected	Observed	Expected	Observed	Global fit [2105.00006]
C_{tG}	[-0.44, 0.44]	[-0.68, 0.21]	[-0.41, 0.42]	[-0.63, 0.20]	[0.007, 0.111]
$C_{tq}^{(8)}$	[-0.35, 0.35]	[-0.30, 0.36]	[-0.35, 0.36]	[-0.34, 0.27]	[-0.40, 0.61]

[ATLAS-CONF-2021-031]

single top operators

Linear

$$O_{Qq}^{3,1} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i \gamma^\mu \tau^I q_i)$$

$$O_{\phi Q}^{3} = (\phi^\dagger \, i\overleftrightarrow{D}_\mu^I \, \phi)(\bar{Q}\gamma^\mu \tau^I Q)$$

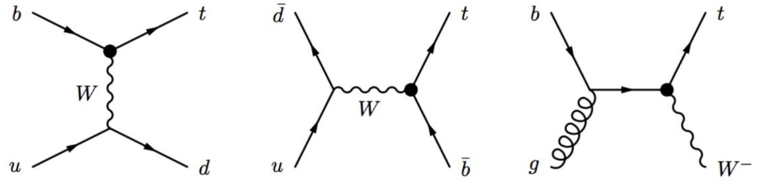
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I$$

Quadratic

$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$$

$$O_{\phi tb} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{t}\gamma^\mu b)$$

$$O_{bW} = (\bar{Q}\sigma^{\mu\nu} b)\, \tau^I \phi \, W_{\mu\nu}^I$$



(t-channel) (s-channel) (tW)

$\frac{s}{m_W^2}$

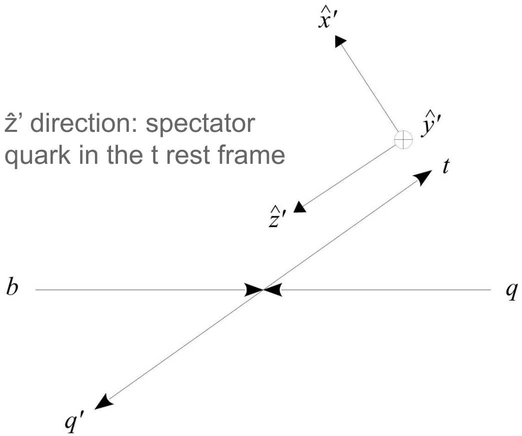
Linear

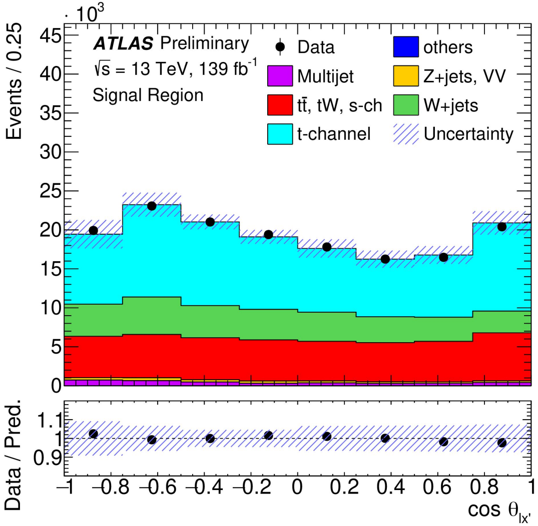
	SM	$C_{Qq}^{3,1}$	$C_{\phi Q}^{3}$	C_{tW}	$C_{Qq}^{3,8}$	$C_{\phi tb}$	C_{bW}
SM	1	$\frac{m_W^2}{\Lambda^2}\ln\frac{s}{m_W^2}$	$\frac{v^2}{\Lambda^2}$	$\frac{m_t v}{\Lambda^2}\frac{m_W^2}{s}\ln\frac{s}{m_W^2}$	–	$\propto m_b$	$\propto m_b$
$C_{Qq}^{3,1}$	…	$\frac{s m_W^2}{\Lambda^4}$	$\frac{v^2 m_W^2}{\Lambda^4}\ln\frac{s}{m_W^2}$	$\frac{m_t v m_W^2}{\Lambda^4}$	–	$\propto m_b$	$\propto m_b$
$C_{\phi Q}^{3}$	…	…	$\frac{v^4}{\Lambda^4}$	$\frac{m_t v^3}{\Lambda^4}\frac{m_W^2}{s}\ln\frac{s}{m_W^2}$	–	$\propto m_b$	$\propto m_b$
C_{tW}	…	…	…	$\frac{v^2 m_W^2}{\Lambda^4}$	–	$\propto m_b$	$\propto m_b$
$C_{Qq}^{3,8}$	…	…	…	…	$\frac{s m_W^2}{\Lambda^4}$	–	–
$C_{\phi tb}$	…	…	…	…	…	$\frac{v^4}{\Lambda^4}$	$\frac{m_t v^3}{\Lambda^4}\frac{m_W^2}{s}\ln\frac{s}{m_W^2}$
C_{bW}	…	…	…	…	…	…	$\frac{v^2 m_W^2}{\Lambda^4}$

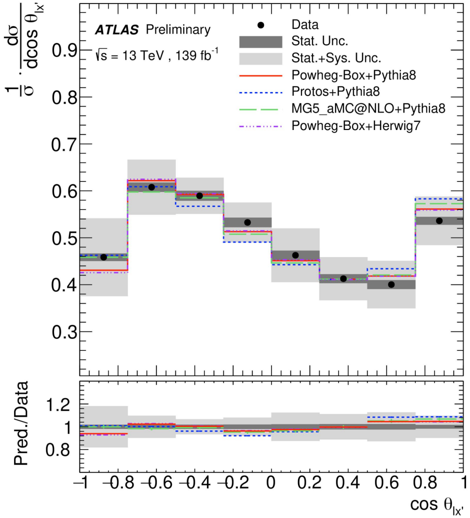
polarization in single top events

- simultaneous measurement of the three components of the top-quark and top-antiquark polarisation vectors in t-channel single top production

ẑ’ direction: spectator quark in the t rest frame

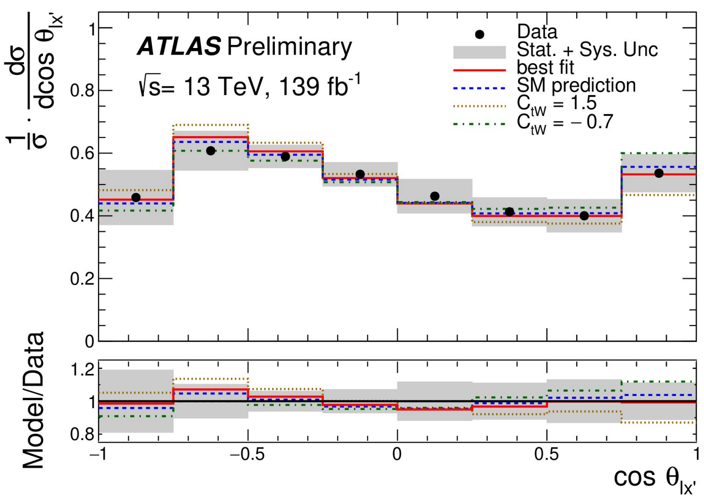






[ATLAS-CONF-2021-027]

polarization in single top events



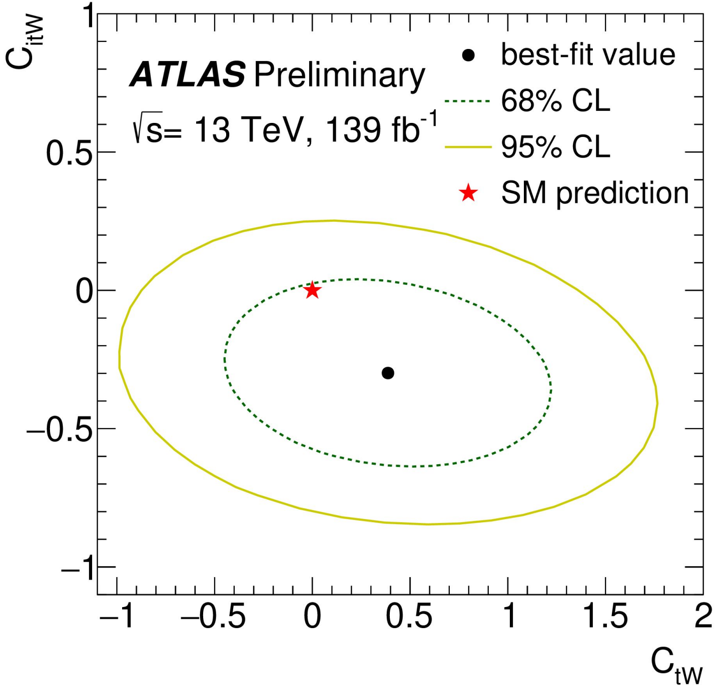
$$\sigma(C_{tW}, C_{itW}) \propto \left| O_{\mathrm{SM}} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|^2_{\text{production}} \cdot \left| O_{\mathrm{SM}} + \frac{C_{tW}}{\Lambda^2} \cdot O_{tW} + \frac{C_{itW}}{\Lambda^2} \cdot O_{itW} \right|^2_{\text{decay}}$$
$$= \sigma_1 + \left(C^1_{tW} \cdot \sigma_2 + C^1_{itW} \cdot \sigma_3 \right) / \Lambda^2$$
$$+ \left(C^2_{tW} \cdot \sigma_4 + C^2_{itW} \cdot \sigma_5 + C^1_{tW} C^1_{itW} \cdot \sigma_6 \right) / \Lambda^4$$
$$+ \left(C^3_{tW} \cdot \sigma_7 + C^3_{itW} \cdot \sigma_8 + C^2_{tW} C^1_{itW} \cdot \sigma_9 + C^1_{tW} C^2_{itW} \cdot \sigma_{10} \right) / \Lambda^6$$
$$+ \left(C^4_{tW} \cdot \sigma_{11} + C^4_{itW} \cdot \sigma_{12} + C^3_{tW} C^1_{itW} \cdot \sigma_{13} + C^1_{tW} C^3_{itW} \cdot \sigma_{14} + C^2_{tW} C^2_{itW} \cdot \sigma_{15} \right) / \Lambda^8.$$

- the effect of non-zero EFT coefficients on the background subtraction was observed to be smaller than the measurement uncertainties

[ATLAS-CONF-2021-027]

polarization in single top events

	C_{tW}		C_{itW}	
	68% CL	**95% CL**	**68% CL**	**95% CL**
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]



[ATLAS-CONF-2021-027]

$t\bar{t}V$ operators

- **ttbar+Z/γ**: access to **neutral top-EW vertex** ttZ/ttγ

"Dim-4"

$$O^1_{\phi Q} = (\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi)(\bar{Q}\gamma^\mu Q)$$

$$O^3_{\phi Q} = (\phi^\dagger\, i\, \overleftrightarrow{D}^I_\mu\, \phi)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\phi t} = (\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi)(\bar{t}\gamma^\mu t)$$

Dipole

$$^\ddagger O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\, \tilde{\phi}\, B_{\mu\nu}$$

$$^\ddagger O_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\, \tau^I \tilde{\phi}\, W^I_{\mu\nu}$$

$$O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\, \tilde{\phi}\, G^A_{\mu\nu}$$

Dofs

$$C^-_{\phi Q} \equiv C^1_{\phi Q} - C^3_{\phi Q}$$

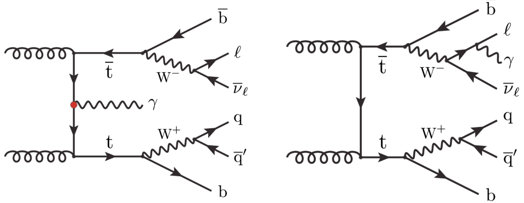
$$C_{tZ} \equiv -s_w C_{tB} + c_w C_{tW}$$

$$C_{tA} \equiv c_w C_{tB} + s_w C_{tW}$$

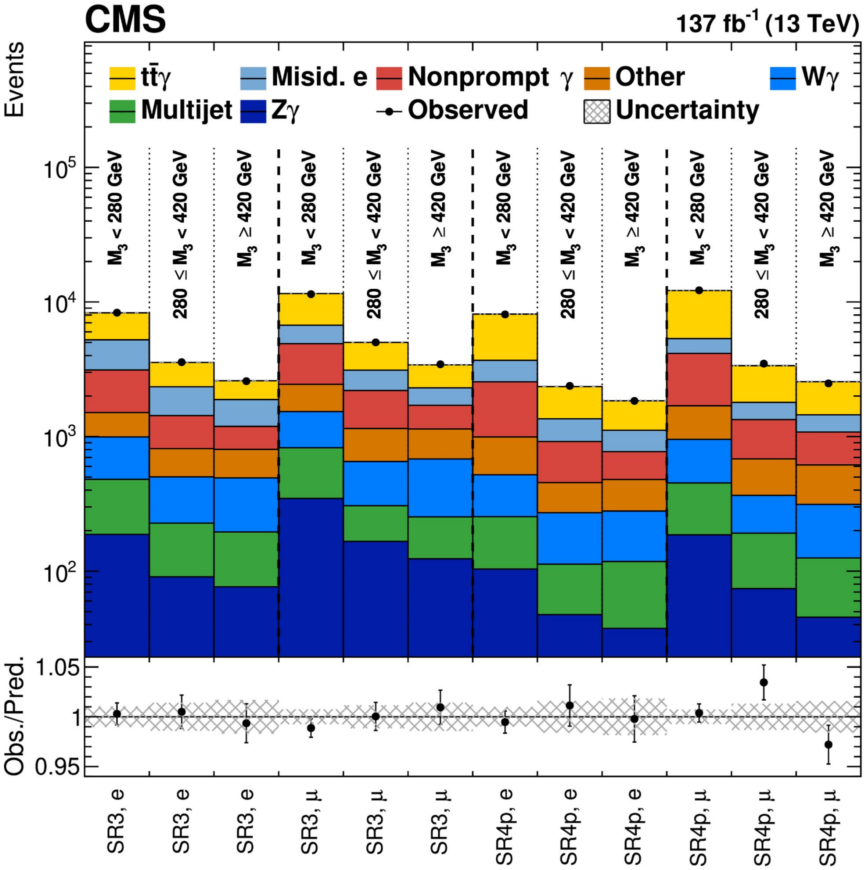
[slide by Cen Zhang]

$t\bar{t}V$ operators: $t\bar{t}\gamma$

- single lepton + photon events

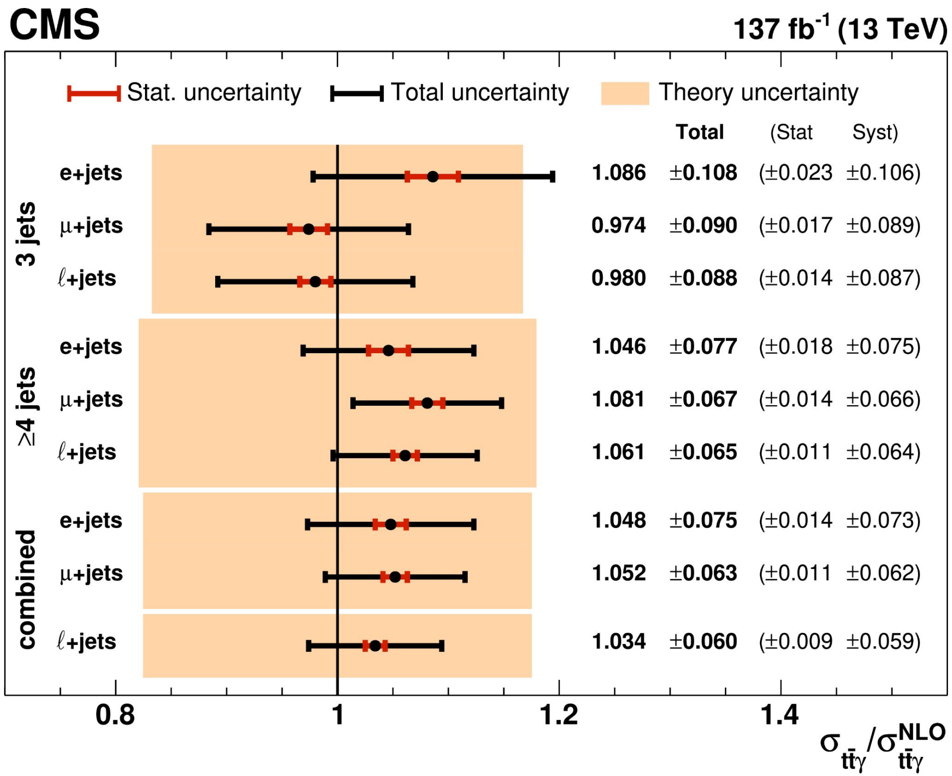


Region		N_ℓ	N_j	N_b	N_γ	Other requirements
SR3p	SR3	1	3	≥1	1	
	SR4p	1	≥4	≥1	1	
LM3p	LM3	1	3	0	1	$m(e,\gamma) < m_Z - 10\,\text{GeV}$, $m(\mu,\gamma) < m_Z$
	LM4p	1	≥4	0	1	$m(e,\gamma) < m_Z - 10\,\text{GeV}$, $m(\mu,\gamma) < m_Z$
HM3p	HM3	1	3	0	1	$m(e,\gamma) > m_Z + 10\,\text{GeV}$, $m(\mu,\gamma) > m_Z$
	HM4p	1	≥4	0	1	$m(e,\gamma) > m_Z + 10\,\text{GeV}$, $m(\mu,\gamma) > m_Z$
misDY3p	misDY3	1	3	0	1	$\lvert m(e,\gamma) - m_Z\rvert \leq 10\,\text{GeV}$
	misDY4p	1	≥4	0	1	$\lvert m(e,\gamma) - m_Z\rvert \leq 10\,\text{GeV}$



[CERN-EP-2021-117]

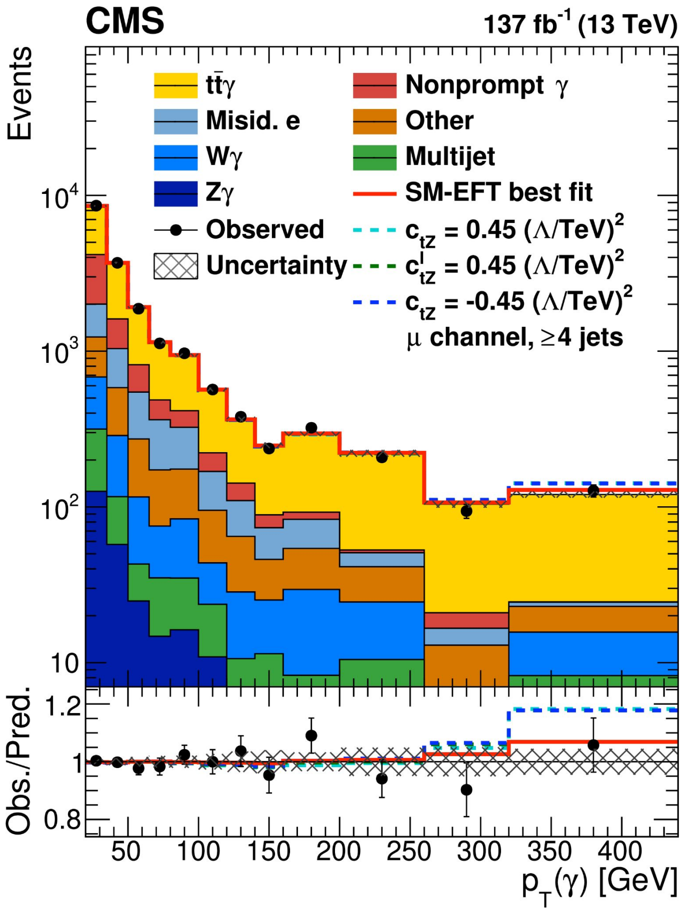
$t\bar{t}V$ operators: $t\bar{t}\gamma$



[CERN-EP-2021-117]

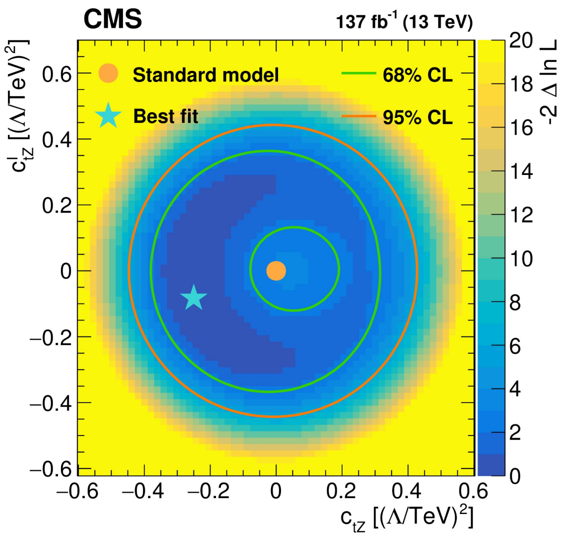
$t\bar{t}$V operators: $t\bar{t}\gamma$

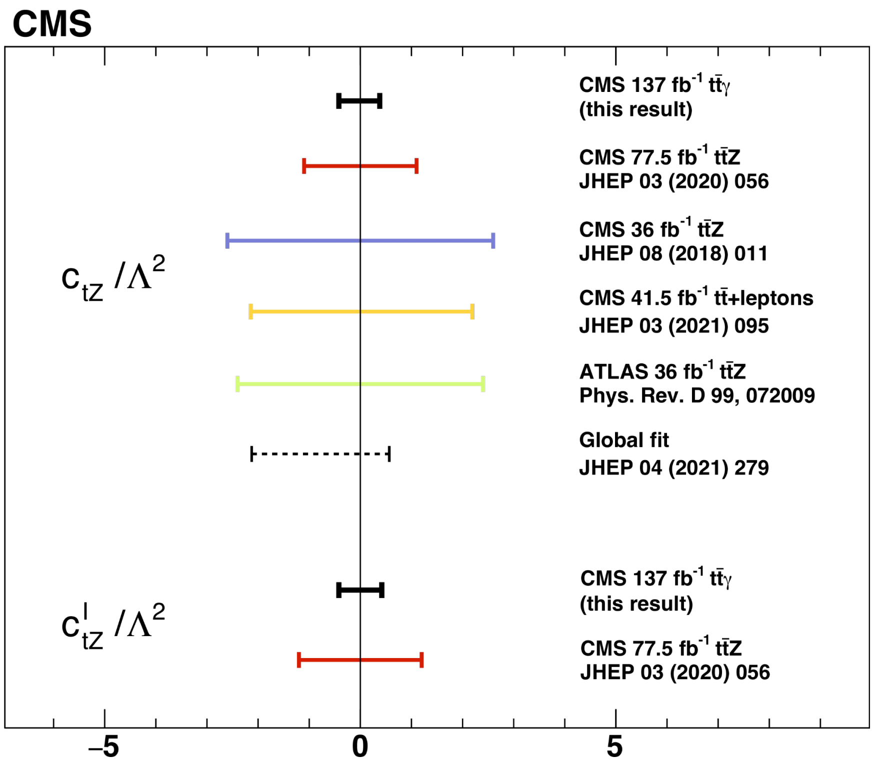
$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right),$$
$$c_{tZ}^{I} = \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right),$$
$$c_{t\gamma} = \mathrm{Re}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right),$$
$$c_{t\gamma}^{I} = \mathrm{Im}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right),$$



[CERN-EP-2021-117]

$t\bar{t}V$ operators: $t\bar{t}\gamma$





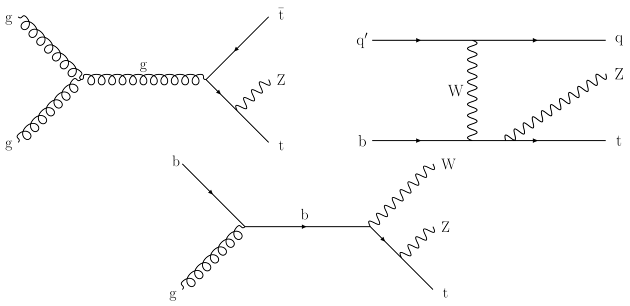
[CERN-EP-2021-117]

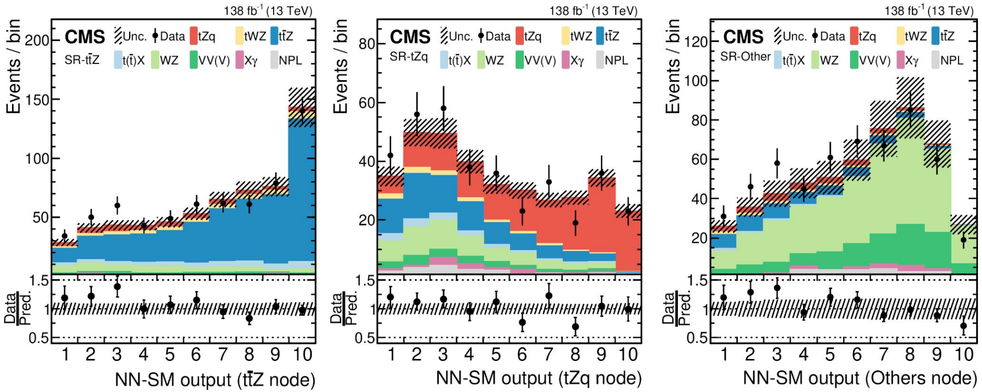
$\mathrm{t\bar{t}V}$ operators: $\mathrm{t\bar{t}Z}$

- targeting events with 3 or 4 charged leptons

Selection requirement	SR-3ℓ	SR-$\mathrm{t\bar{t}Z}$-4ℓ	WZ CR	ZZ CR
Lepton multiplicity	=3	=4	=3	=4
$m_{3\ell} - m_{\mathrm{Z}}$	—	—	>15 GeV	—
Z boson candidates multiplicity	=1	=1	=1	=2
Jet multiplicity	≥2	≥2	—	—
b jet multiplicity	≥1	≥1	=0	—
$p_{\mathrm{T}}^{\mathrm{miss}}$	—	—	>50 GeV	—

- NNs used to separate signal from back. and to enhance the sensitivity to new phenomena arising from the EFT operators of interest





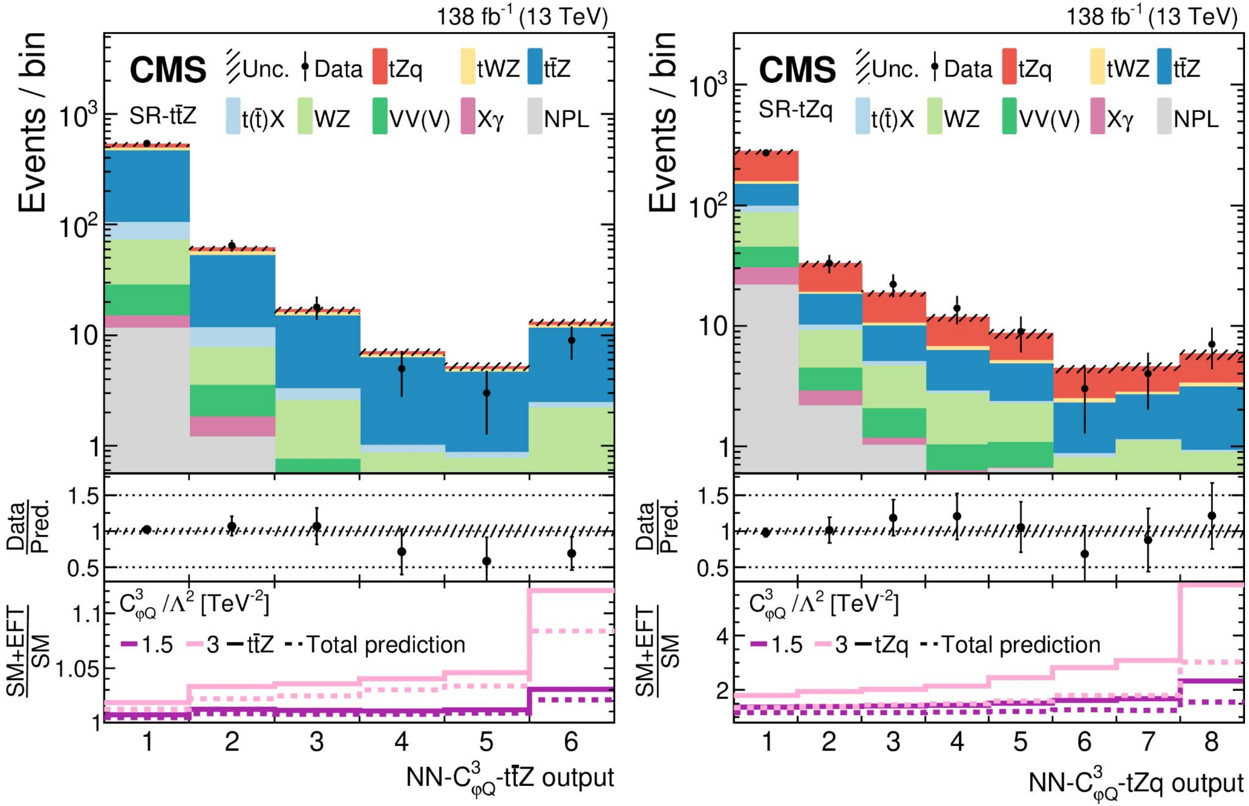
[CERN-EP-2021-126]

$\mathrm{t\bar{t}V}$ operators: $\mathrm{t\bar{t}Z}$

Operator	WC	Mapping to Warsaw-basis coefficients
$\mathcal{O}_{\mathrm{tZ}}$	c_{tZ}	$\mathrm{Re}\{-s_{\mathrm{W}} c_{\mathrm{uB}}^{(33)} + c_{\mathrm{W}} c_{\mathrm{uW}}^{(33)}\}$
$\mathcal{O}_{\mathrm{tW}}$	c_{tW}	$\mathrm{Re}\{c_{\mathrm{uW}}^{(33)}\}$
$\mathcal{O}_{\varphi\mathrm{Q}}^{3}$	$c_{\varphi\mathrm{Q}}^{3}$	$c_{\varphi\mathrm{q}}^{3(33)}$
$\mathcal{O}_{\varphi\mathrm{Q}}^{-}$	$c_{\varphi\mathrm{Q}}^{-}$	$c_{\varphi\mathrm{q}}^{1(33)} - c_{\varphi\mathrm{q}}^{3(33)}$
$\mathcal{O}_{\varphi\mathrm{t}}$	$c_{\varphi\mathrm{t}}$	$c_{\varphi\mathrm{u}}^{(33)}$

Variable	NN-SM	NN-c_{tZ}-tZq	NN-c_{tZ}-$\mathrm{t\bar{t}Z}$	NN-c_{tW}-tZq	NN-c_{tW}-$\mathrm{t\bar{t}Z}$	NN-$c_{\varphi\mathrm{Q}}^{3}$-tZq	NN-$c_{\varphi\mathrm{Q}}^{3}$-$\mathrm{t\bar{t}Z}$	NN-5D-tZq	NN-5D-$\mathrm{t\bar{t}Z}$
$p_{\mathrm{T}}^{\mathrm{Z}}$	—	✓	✓	✓	✓	✓	✓	✓	✓
$\eta(\mathrm{Z})$	✓	✓	✓	—	—	✓	—	—	✓
$\Delta\phi(\ell_1^{\mathrm{Z}}\ell_2^{\mathrm{Z}})$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$p_{\mathrm{T}}(\mathrm{t})$	✓	✓	✓	—	✓	✓	—	✓	✓
$\eta(\mathrm{t})$	—	✓	✓	✓	✓	✓	—	—	✓
$m(\mathrm{t},\mathrm{Z})$	—	—	—	—	—	—	—	—	—
$\lvert\eta(j')\rvert$	✓	—	—	—	—	—	—	✓	—
$p_{\mathrm{T}}(j')$	✓	✓	—	✓	—	—	—	—	—
$\Delta R(b,\ell_{\mathrm{t}})$	—	✓	—	✓	—	—	—	—	—
$\Delta R(j',\ell_{\mathrm{t}})$	✓	—	—	—	—	—	—	—	—
$\Delta R(\mathrm{t},\mathrm{Z})$	—	✓	✓	✓	—	✓	—	—	✓
$\Delta\eta(\mathrm{Z},j')$	—	✓	—	—	—	—	—	✓	—
ΔR between t and the closest lepton	—	✓	—	✓	—	—	—	—	—
ΔR between j' and the closest lepton	—	—	—	—	—	—	—	✓	—
$m_{3\ell}$	✓	—	—	—	✓	—	✓	—	✓
$m_{\mathrm{T}}^{\mathrm{W}}$	✓	✓	✓	—	—	—	—	—	✓
$p_{\mathrm{T}}^{\mathrm{miss}}$	✓	—	—	—	—	—	—	—	—
Lepton asymmetry	✓	—	—	✓	✓	—	—	✓	—
$\cos\theta_{\mathrm{Z}}^{\star}$	—	—	✓	—	—	✓	—	—	✓
Max. p_{T} among jet pairs	—	—	—	—	—	—	✓	—	✓
Max. DEEPJET discriminant	✓	—	—	—	—	—	—	—	—
b jet multiplicity	✓	—	—	—	—	—	—	—	—
Three-momenta of the three leading leptons	✓	—	—	—	—	—	—	—	—
Three-momenta of the three leading jets	✓	—	—	—	—	—	—	—	—
DEEPJET discriminants of the three leading jets	✓	—	—	—	—	—	—	—	—
Number of variables	33	11	8	8	6	7	4	7	10

$\overline{t}tV$ operators: $\overline{t}tZ$



[CERN-EP-2021-126]

$t\bar{t}V$ operators: $t\bar{t}Z$

Fit configuration	Region					
	SR-tZq	SR-$t\bar{t}Z$	SR-Others	SR-$t\bar{t}Z$-4ℓ	CR WZ	CR ZZ
1D c_{tZ}	NN-c_{tZ}-tZq	NN-c_{tZ}-$t\bar{t}Z$				
1D c_{tW}	NN-c_{tW}-tZq	NN-c_{tW}-$t\bar{t}Z$				
1D $c^{3}_{\varphi Q}$	NN-$c^{3}_{\varphi Q}$-tZq	NN-$c^{3}_{\varphi Q}$-$t\bar{t}Z$	m_{T}^{W}	Counting experiments		
1D $c^{-}_{\varphi Q}$	NN-SM (tZq node)	NN-SM ($t\bar{t}Z$ node)				
1D $c_{\varphi t}$	NN-SM (tZq node)	NN-SM ($t\bar{t}Z$ node)				
2D and 5D	NN-5D-tZq	NN-5D-$t\bar{t}Z$				

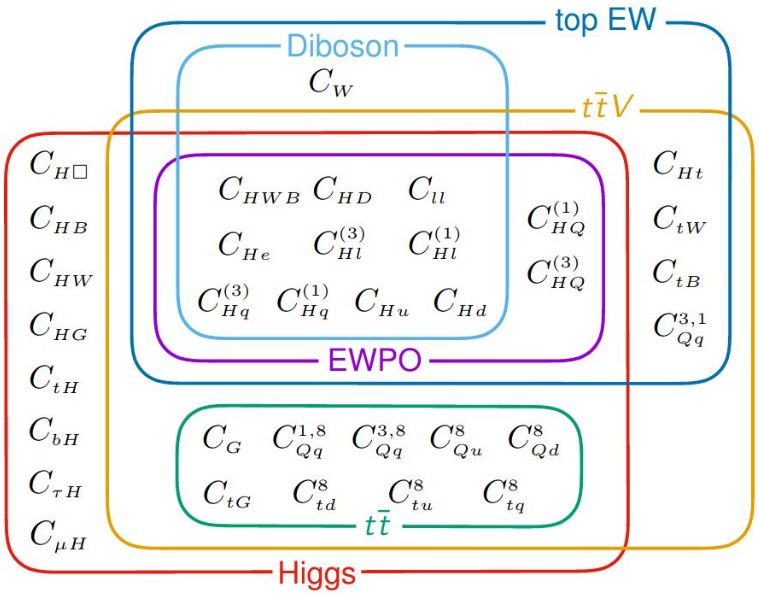
WC/Λ^2 [TeV^{-2}]	95% CL confidence intervals			
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^{3}_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^{-}_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$

[CERN-EP-2021-126]

summary

- In the absence of evidence for BSM physics in collider data (so far..), EFT is a powerful tool to look for subtle deviations from the SM in data

- EFT in the top quark sector (and beyond) is an hot topic, with the experimental and the theory communities engaged
    - focus changing to global fits



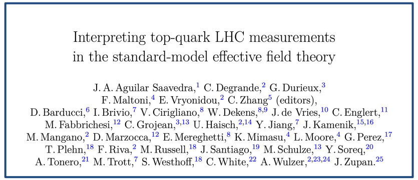
Thanks for your attention

Questions?

you can always reach me at nuno.castro@cern.ch

many thanks to the colleagues from ATLAS, CMS, LHC *top* WG and LHC *EFT* WG for the stimulating discussions, ideas and material for this talk

Effective field theory
LHC *top* WG


Interpreting top-quark LHC measurements
in the standard-model effective field theory

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M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16]
M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17]
T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
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- LHC *top* WG has been considering EFT interpretations for a number of years (first papers in 2008-9)
  - Main highlight is https://arxiv.org/abs/1802.07237: 'top EFT white paper'
  - Wonderful example of collaboration across theorists with input from experimentalists!
- Main points from that document
  - Warsaw basis
  - 3 different flavour assumptions
    - Default: minimal flavour violation in the quark sector (less and more restrictive are considered as alternatives): $U(2)_q \times U(2)_u \times U(2)_d$
  - FCNC is treated separately
  - Identify the linear combinations of Warsaw-basis operators that appear in interferences with SM amplitudes and in interactions with physical fields after electroweak symmetry breaking (notation and normalisation agreed upon)
- Main limitations
  - "Our discussion exclusively concerns processes involving at least a top quark" → work towards global fits (LHC *EFT* WG)
  - For now: tree-level description only
    - NLO work ongoing

Effective field theory

LHC *EFT* WG

- Dedicated meetings in 6 areas:
  - Area 1: EFT Formalism
  - Area 2: Predictions and Tools
  - Area 3: Experimental Measurements and Observables
  - Area 4: Fits and Related Systematics
  - Area 5: Benchmark Scenarios from UV Models
  - Area 6: Flavour Physics

- Write-ups being prepared

June 2021
- 28 Jun Area 1, EFT formalism

May 2021
- 03 May 2nd General Meeting of the LHC EFT Working Group

April 2021
- 12 Apr Area 6 meeting: Heavy flavour aspects in EFT fits

February 2021
- 22 Feb Areas 3&4 meeting: experimental measurements, fits and related systematics
- 08 Feb Area 5 meeting: Benchmark scenarios from UV models

January 2021
- 27 Jan Area 4 meeting: fits and related systematics
- 19 Jan Area 1, EFT formalism: follow-up meeting
- 11 Jan Area 3 meeting: experimental measurements and observables

December 2020
- 14 Dec Area 2 meeting: predictions and tools
- 07 Dec Area 1 meeting: EFT formalism

October 2020
- 19 Oct - 20 Oct 1st General Meeting of the LHC EFT Working Group

April 2020
- 17 Apr LHC EFT Working Group: preliminary open discussion

https://indico.cern.ch/category/12671/

Effective field theory

LHC *EFT* WG

- Area 1: EFT Formalism
  - Common conventions, translations, common EW inputs
    - scheme $\{G_{\mu}, m_Z, m_W\}$ is preferred
    - conversion rules exist
  - Flavour structures, classes of BSM, symmetries
  - Truncation, uncertainties, validity
    - SMEFT truncation of interest is at the level of dim-6 operators. Two proposals:
    - linear+quadratic dim-6 as nominal + compare with linear-only dim-6
    - linear dim-6 as nominal + uncertainty constructed from known quadratic dim-6 and dim-8 contributions
    - provide experimental results as functions of the maximal energy probed in the data employed, Ecut
    - no final recommendations so far
  - Theory constraints - unitarity, positivity, incorporation in fits

Effective field theory

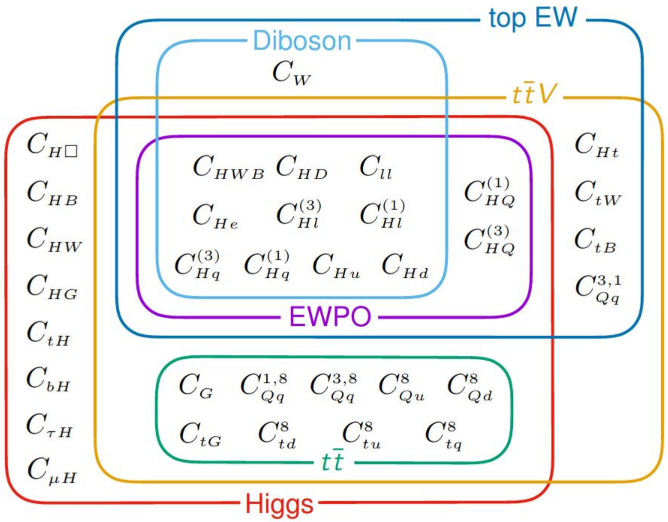
LHC *EFT* WG

- Area 2: Predictions and Tools
    - Presented review of the tools:
        - UFO models: SMEFTsim, SMEFT@NLO
    - MC generators for SMEFT: MadGraph5_aMC@NLO, Sherpa, JHUGen, Powheg, VBF@NLO
    - LHC *top* WG guidelines for EFT: dim6top and SMEFTsim
        - Is dim6top deprecated by the other two UFO models?
    - ATLAS plans to use mainly SMEFTsim (flavour symmetry “topU3l”) and, if needed, SMEFT@NLO
    - Experimentalists concerns - expressed at the LHC *EFT* WG meetings
        - higher order term (prod+decay)
        - NLO
        - reweighting
        - assumptions
        - EFT gluon interactions

Effective field theory

LHC *EFT* WG

- Area 3: Experimental Measurements and Observables
  - Discussed different approaches for EFT interpretations of measurements:
    - differential cross sections
    - dedicated analyses
    - matrix-element observables
    - machine-learning observables
  - Topics for the write-up:
    - establish a detailed map between EFT
    - operators and experimental observables
    - determine relative sensitivity of observables to operators
    - performing measurements & interpretations: pros and cons of various analyses techniques



Effective field theory

LHC *EFT* WG

- Area 4: Fits and Related Systematics
  - Reviewed the status of fitting frameworks and their validation: EFTfitter, Fitmaker, HEPfit, SFitter, SMEFiT, ...
  - Reviewed the status of the fitting experience by ATLAS and CMS
  - Presentation of public experimental results
    - public information should allow for reinterpretations
- Area 5: Benchmark Scenarios from UV Models
  - How do we best interpret EFT analysis in explicit models?
  - A UV model predicts WCs in terms of its parameters - matching.
  - The key theoretical aspect is matching the UV model onto EFT at high accuracy
  - The dawn of automated one-loop matching tools
    - SuperTracer: arXiv:2012.08506
    - STrEAM: arXiv:2012.07851
  - Goal: set benchmark scenarios:
    - Interesting phenomenology
    - Validation of different tools.

Effective field theory

LHC *EFT* WG

- Area 6: Flavour Physics
  - It is a key to a global fit
  - Most of the 2499 dim-6 operators in SMEFT are flavourful
  - Flavor physics reaches into most dimensions
  - Impact of flavour on top/H/EW
    - Indirect constraints on flavor-less operators
    - Flavorful New Physics can manifest itself in different observables
    - To be able to address these cases it is important to perform EFT fits keeping the complete flavor dependence

SMEFT@NLO vs. SMEFTsim

	SMEFT@NLO 1.0	**SMEFTsim topU3l**	**SMEFTsim top**
Quark sector flavor sym.	$U(2)_q \times U(3)_d \times U(2)_u$	$U(2)_q \times U(2)_d \times U(2)_u$	$U(2)_q \times U(2)_d \times U(2)_u$
Lepton sector flavor sym.	$[U(1)_l \times U(1)_e]^3$	$U(3)_l \times U(3)_e$	$[U(1)_l \times U(1)_e]^3$
QCD order	LO or NLO	LO	LO
CP violating terms	omitted	present	present
Summary	Most operators identical to SMEFTsim, there are few differences in the sign convention or basis rotations	More operators with b-quark fields wrt SMEFT@NLO	More operators with b-quark fields wrt SMEFT@NLO

$t\bar{t}V$ operators: $t\bar{t}Z$

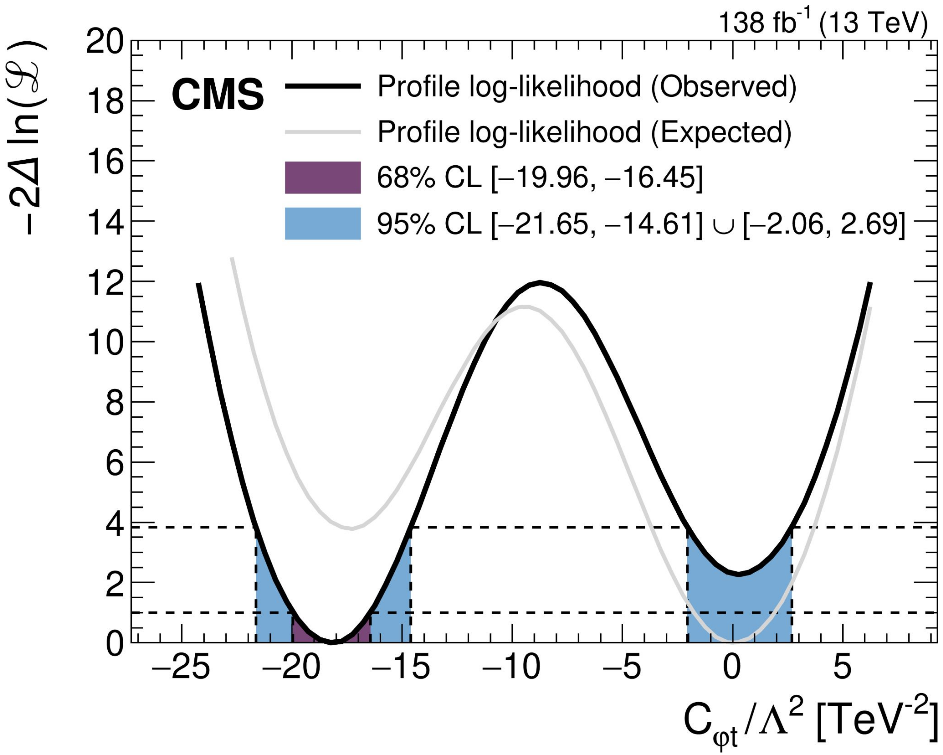
impact of systematics on the Wilson coefficients

Source	c_{tZ}	c_{tW}	$c^{3}_{\varphi Q}$	$c^{-}_{\varphi Q}$	$c_{\varphi t}$
tZq normalization	<0.1	<0.1	1.2	0.1	0.8
$t\bar{t}Z$ normalization	0.6	<0.1	0.4	37	38
tWZ normalization	0.1	0.1	<0.1	0.7	2.1
Background normalizations	<0.1	<0.1	6.9	3.6	6.8
NPL background estimation	1.4	0.2	5.6	0.3	3.8
Jet energy scale	<0.1	<0.1	0.8	0.7	2.3
Jet energy resolution	<0.1	<0.1	<0.1	<0.1	1.4
p_{T}^{miss}	<0.1	<0.1	<0.1	<0.1	0.2
b tagging	<0.1	<0.1	0.9	2.0	0.3
Other (experimental)	<0.1	<0.1	1.6	0.8	0.6
Lepton identification and isolation	0.4	0.4	1.2	2.2	0.8
Theory	2.1	1.1	0.4	0.9	0.9

measurement dominated by systematics

[CERN-EP-2021-126]

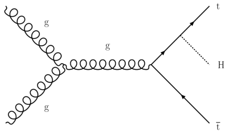
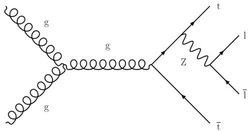
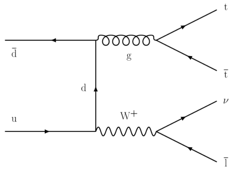
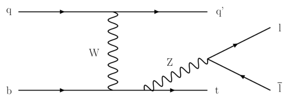
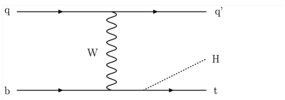
$t\bar{t}V$ operators: $t\bar{t}Z$
double-minima structure

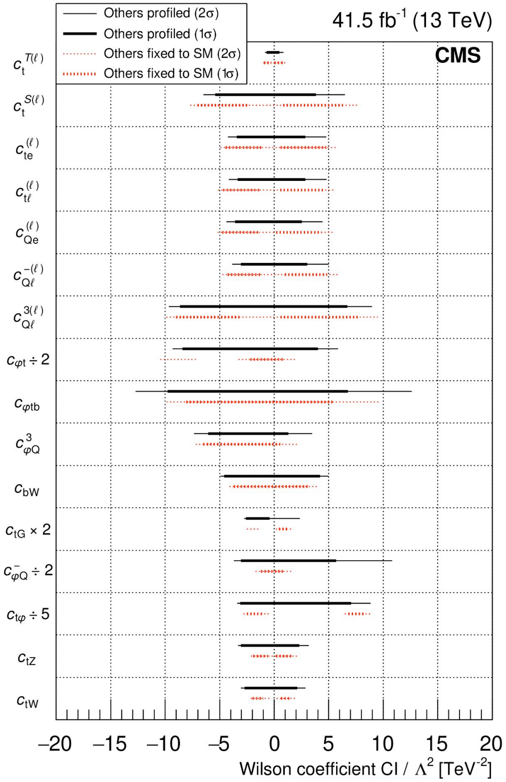


[CERN-EP-2021-126]

Effective field theory in the top quark sector
towards more general fits

- selecting events with either 2 leptons with the same charge or more than two leptons (+ jets, including b-tagged ones)



[CERN-EP-2020-211]